PULSE SHARPENING IN FERRITE TRANSMISSION LINES

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Abstract

Pulse sharpening effects in ferrite transmission lines may be used to obtain kV pulses with ns risetime.   The exact description of the sharpening effect requires complex shock wave analysis[1]. In this paper an approximate but useful physical model is discussed. The ferrite is treated as a lossy but linear transmission line from which equivalent design results are obtained. In many instances the nonlinear effects present are confined to a region which is small compared to the total transmission length, which makes the linear approximation more plausible. Preliminary experimental results, based on a 130 cm long line, are in accord with the predictions of the model.

Introduction

In recent years an increasing need has arisen for kV pulsers with ns risetimes. In the area of pulsers for mm wave tubes, for example, extremely narrow pulse widths (< 5 ns) are desired for improved resolution. At the same time pulse repetition rates as high as 20 kHz, with pulse voltage and current amplitudes up to 15 kV and 1000 A, respectively, are required. These simultaneous requirements place tremendous burdens on the switch, which is the key element in the design of such a pulser. Switches now available do not simultaneously satisfy the risetime, PRR, and power requirements. For example spark gaps satisfy the risetime and peak power requirements, but are unable to satisfy the PRR requirement.

A promising solution to the switch problem is the use of a slower risetime switch in combination with a ferrite pulse sharpener. The incorporation of a ferrite pulse sharpener into the discharge circuit has the advantage of simultaneously providing fast risetime, large PRR, and large peak power levels. There are disadvantages, however, and these are added circuit complexity and bulk, as well as lowered circuit efficiency caused by the need for bias current. Nevertheless the ferrite pulse sharpener has potential in an area where there are few technological alternatives.

In recent years the bulk of the scientific literature on ferrite pulse sharpeners has appeared in the USSR. In particular, the work by Kataev[1] emphasized the shock wave aspects of the wave propagating in the ferrite. Exact analysis has indicated the formation of shock waves under a variety of conditions, and such waves are important in the interpretation of pulse sharpening effects.

In this report an elementary model for the pulse sharpening effect is presented, wherein the ferrite is treated as a lossy but linear transmission line. A simplifying feature is introduced with the idea of a spin saturation front, which travels along the length of the ferrite. The shock wave nature of the problem is pointed out, but emphasis is placed on simple and useful solutions which are possible without explicitly solving the shock wave problem.

Outline of Model

We consider a ferrite transmission line which is uniformly magnetized in the direction transverse to the direction of propagation (Fig. 1). A transmission line without ferrite, with impedance Z_o, is connected to the input terminals of the ferrite. A pulse with risetime T_R is incident upon the ferrite. The polarity of the magnetic field of the pulse is opposite to that of the magnetization. As a consequence the pulse will see a large RF impedance consisting of an inductance, as well as a resistive component caused by dissipation in the ferrite. For the most part the signal will be reflected, although a substantial percentage of the incident energy will propagate into the ferrite. The region close to the start of the ferrite line will not continually appear as a large impedance, however. Eventually this portion of the ferrite will suddenly reach saturation. When this happens the large impedance will suddenly decrease to the saturated impedance,

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14. ABSTRACT

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Z_s, which by design is chosen equal to Z_0, the input impedance. As shown in Fig. 1, this process continues, so that a "spin saturation front" propagates along the length of the ferrite. The velocity of this front will increase as the pulse amplitude is increased. The ferrite line is designed such that, when the front reaches the end of the ferrite line (i.e., the entire length of the ferrite is completely magnetized in the opposite direction) the pulse is near or at its plateau value. This will occur at t = T_R ignoring transit time effects, i.e., assuming the velocity in the saturated region is much larger than the velocity of the spin saturation front.

The advance of the spin saturation front must be distinguished from the region of magnetic field propagating beyond the spin saturation front. Such field penetration arises from the inherent delay which exists between the onset of the magnetic field and the time needed for the spins to change direction. The field penetration is confined to a "propagation width," Fig. 2. In this region the magnetization changes continuously between the two oppositely saturated states. At the spin saturation front the magnetization is aligned with the incident magnetic field, and the changeover to the lower saturation impedance is imminent. At the far end of the propagation width the field signal h_f has just arrived and the magnetization is still saturated and opposite to that of the field. The field is also shown as terminating abruptly at the end of the propagation width. This simplifies the model but in fact dispersion effects, which result from the presence of loss in the transmission line, will tend to cause the field to decrease more gradually.

As implied in Fig. 2 the field propagating beyond the spin reversal front will be dampened, resulting from the dissipation which accompanies the rotation of the spins. The propagation width, as well as the amount of damping, will vary, depending on the ferrite loading and numerous other parameters. In most cases the field penetration will be small, on the order of a few centimeters, compared to the total length of the ferrite line which is typically one meter long. The relatively small region to which the propagation is confined makes plausible certain simplifications in the description of pulse sharpening, without resorting to detailed shock wave analysis.

Analysis of Model

For concreteness we consider a coaxial transmission line in which the ferrite fills the entire space between inner and outer conductors. The analysis may be easily extended to the case where the line is partially filled with ferrite, in which we have concentric dielectric and ferrite sleeves. It is also assumed the ferrite transmission line is connected to a load Z_L while the input is connected to another line of impedance Z_0 (Fig. 3).

In the saturated region of the line the ferrite has an inductance per unit length (L_s) and a capacitance per unit length (C_s). L_s, C_s, and Z_s are given by standard expressions for the coaxial line.

When the ferrite magnetization is not aligned with the incident magnetic field, the ferrite will appear as a large impedance relative to the saturated impedance. When this happens most of the input energy will be reflected although a significant percentage of the energy will be transmitted into the ferrite. In order to ascertain the degree of reflection, one must calculate the electrical parameters associated with the ferrite line, L_f, C_f, R_f (Fig. 3).

The transmission line parameters are a function of the physical mechanisms by which the magnetization aligns itself with the magnetic field, h_f. The mechanism which appears to prevail is the Gilbert form of the Landau Lifschitz equation[2] from which the time dependence of the magnetization is given by (gaussian units)

$$\frac{dM_z}{dt} = \frac{2M_s\, h_f}{S}\left[1 - \frac{M_z^2}{M_s^2}\right] \qquad (1)$$

where M_z is the magnetization along the applied field, M_s is the saturation magnetization and S is the switching constant. Using the approximation given by Gyorgy[3] the switching time T_0, for M_z to go from $-M_s$ to $+M_s$, is given by

$$T_0 = \frac{S}{h_f} \qquad (2)$$

Thus T_0 is inversely proportional to the magnetic field. Using Eqs. (1), (2), and the circuit of Fig. 3, calculation of the network parameters L_f, C_f, gives

$$L_f = \frac{32\,\pi^2(d-a)\,M_s}{\ell_m\, h_f}\times 10^{-7}\ \frac{h}{m} \qquad (3)$$

$$R_f = \frac{32\,\pi^3(d^2 - a^2)\,M_s}{\ell_m^2\, S}\times 10^{-7}\ \frac{\Omega}{m} \qquad (4)$$

where d and a are the outer and inner radii of the ferrite, respectively, and ℓ_m is the mean magnetic length. In all equations the magnetization, magnetic field, and S are given in gaussian units. All other quantities are in MKS.

In calculating L_f and R_f, using Eq.(1), we have assumed the time averaged quantity for M_z, i.e., $M_z = 0$. In a sense this amounts to treating the entire propagation width as the load seen by the incident wave, since M_z varies from $+M_s$ to $-M_s$ in the region. Intuitively this appears to be a reasonable assumption since this length is usually small compared to the total ferrite length and is also small, or at least comparable, to the wavelengths corresponding to the frequencies present

in the incident wave.

The final network parameter needed to describe the high impedance ferrite is the capacitance per units length C_f. No calculation is required here however since we have assumed that the magnetic properties are uncoupled from the dielectric properties. Thus C_f will be unchanged from the saturated capacitance C_s.

Once the network components L_f, R_f, and C_f are known, one may calculate various transmission line properties such as the impedance Z_f, the reflection coefficient Γ, the propagation constant γ_f, and other quantities, using steady state transmission line expressions with frequency ω. The phase velocity v_p is obtained from ω/β_f where β_f is the imaginary part of γ_f. Another important velocity is that of the spin saturation front, v_f, which is obtained by relating the energy delivered by the pulse to the energy needed to redirect the spins contained in the propagation width, L_o. The propagation width is defined by $L_o = v_p T_o$. A second important length is $L_a = 1/\alpha_f$ where α_f is the real part of γ_f. When $L_a < L_o$ substantial attenuation occurs. When $L_a > L_o$ the loss is small. When the pulse is introduced at the start of the line the propagation width will be relatively large since the field in the ferrite is small. As the pulse increases in amplitude v_f will increase and the spin saturation front will catch up with the propagation front. The residual field penetration at the end of the line will have a time duration of T_o, given by Eq. (2), which represents the risetime limitation.

Model Approximations

In order to obtain mathematically tractable results several approximations have been made. The more important of these will be discussed briefly.

An important approximation is the neglect of shock waves. In the propagation region it was shown that the permeability is inversely proportional to the signal level. The lower permeability region near the spin saturation front thus supports a faster wave compared to the higher permeability near the end of the propagation region. As a result the faster waves will catch up with the slower waves, compressing the propagation region. A knowledge of such waves may be derived from the nonlinear differential equations which apply.

A second approximation is the application of the steady state solution to deal with a problem which is transient in nature, i.e., we are dealing with a pulse rather than the case of a single frequency. Further, the line is lossy and thus dispersion effects will occur. Laplacian techniques may be applied to solve such a problem, although the details are cumbersome. Although the transient calculation is not done here, one can surmise the dispersion effects at least by examining various frequencies, ω, such that $\omega \lesssim \omega_0$ where $\omega_0 = 2\pi/T_R$. Since we are interested in the fast risetime response, our interest will be centered on the higher frequencies since these

frequencies are responsible for the fast rise-time. In addition one must take into account pulse broadening which results from motion of spin saturation front relative to the propagation in the saturated region.

Another approximation has to do with the time dependence of the magnetization expressed in Eq. (1). Time average values of L_f have been utilized, and their effect on the solution should be examined. Also the time change in magnetization slows down considerably near extremes $M_z = \pm M_s$. This will impact on the sharpness of the spin saturation front, resulting in a front which has a profile rather than one in which the change is abrupt.

Another important approximation is the neglect of magnetic field accumulation in the propagation region, arising from earlier portions of the pulse risetime. In this analysis it is assumed h_f is solely a function of the field incident on the saturation front and prior fields are ignored. Taking field accumulation into account affects the calculation of T_o as well as the network parameters L_f, R_f.

Computational Results

Computation of several important quantities, based on the model, is given in Fig. 4. In order to obtain numerical results it is assumed the frequency, ω, is given by $2\pi/T_D$ where T_D is the delay time, i.e., the time needed for the spin saturation front to transverse the ferrite. It is assumed the pulse reaches its plateau value the moment it emerges from the ferrite. If transit time effects are ignored $T_D = T_R$.

Fig. 4 shows how v_f, v_p, and T_o change during the pulse risetime incident on the spin saturation front. It is assumed voltage incident on the front, V, has a ramp like dependence, reaching a maximum of 6×10^3 volts at $t = 70$ ns. As anticipated both v_f and v_p increase with signal level, although v_p levels off because of the resistive losses. T_o decreases rapidly with voltage. This is expected since the signal strength becomes large in the propagation width, and this in turn reduces T_o. The value of T_o at $t = 70$ ns is $\approx$ 2.0 ns, which represents the residual risetime emerging from the ferrite line. L_o is approximately 5 cm as it emerges from the ferrite.

The length of the ferrite line L_f is found by integrating v_f. With the present model L_f should be approximately equal to the integral of v_p, denoted by L_p. This ignores corrections arising from the propagation width, which effectively increases L_p. In the case of Fig. 4, for example L_f is 101 cm while L_p is 90 cm.

Experimental Results

A 130 cm long coaxial ferrite line was constructed and tested. The magnetic material is magnesium ferrite, supplied by Trans-Tech, type TTI-3000. The saturation magnetization ($4\pi M_s$) is 3000 gauss, with a remanent induction of 2000 gauss and a coercive force of 0.85 Oe. The ferrite is composed of sleeves each 1.25 cm long, with an OD of 0.5 cm and an ID of 0.25 cm.

The basic circuit for testing the pulse sharpener is shown in Fig. 5. The input switch is a thyratron, JAN 7621, which operates up to 8 kV peak. The cable PFN has a 50 Ω impedance, with the pulsewidth varying from 50 ns to 300 ns. The bias circuit provides current to "set" the ferrite. RF chokes are included to prevent pulse interaction between the bias circuit and the ferrite line. Current in a low inductance load resistor is measured with a Tektronix CT-1 transformer.

When the ferrite was biased in its "set" state very little difference was noticed in the output when the magnetic field exceeded the coercive force of 0.85 Oe. However, when the field was reduced below this value the flux reversal quickly diminished and the output changed accordingly. Pulse sharpening could be obtained with bias currents as low as 0.4 A.

Fig. 6 shows the pulse waveforms with and without bias for a 6 kV charging voltage. The effective magnetization was reduced by lowering the bias current to 0.4 A. The sharpened risetime after correction for instrumentation risetime of 2.5 ns is about 6 ns. The total delay time T_D is approximately 70 ns which includes 35 ns of transit time delay. Experimental results may be compared with the computed results in Fig. 4, assuming the parameter values listed. The model predicts a length of 101 cm and a residual risetime of 2 ns. The discrepancy in risetime is accounted for by dispersion and field accumulation effects, which have been ignored.

The net pulse sharpening can only be determined by comparison of the sharpened pulse with the incident pulse, delivered to 50 Ω, with the ferrite line disconnected. The risetime thus measured was 15 ns, indicating a net improvement of better than 2:1.

Conclusions

A model for the ferrite pulse sharpener based on a lossy but linear transmission line was formulated. Results derived from the model appear to be in reasonable accord with the experiments done on a 130 cm large ferrite line. Further refinements in the model and additional comparison with experimental results are planned.

References

1. I. G. Kataev, "Electromagnetic Shock Waves," Sovietskoye Radio Press, 1963.

2. Kikuchi, "On the Minimum of Magnetization Reversal Time," J. Appl. Phys, Vol. 27, pp. 1352-1357, November 1956.

3. Gyorgy, "Rotational Model of Flux Reversal in Square Loop Ferrites," J. Appl. Phys, Vol. 28, pp. 1011-1015, September 1957.

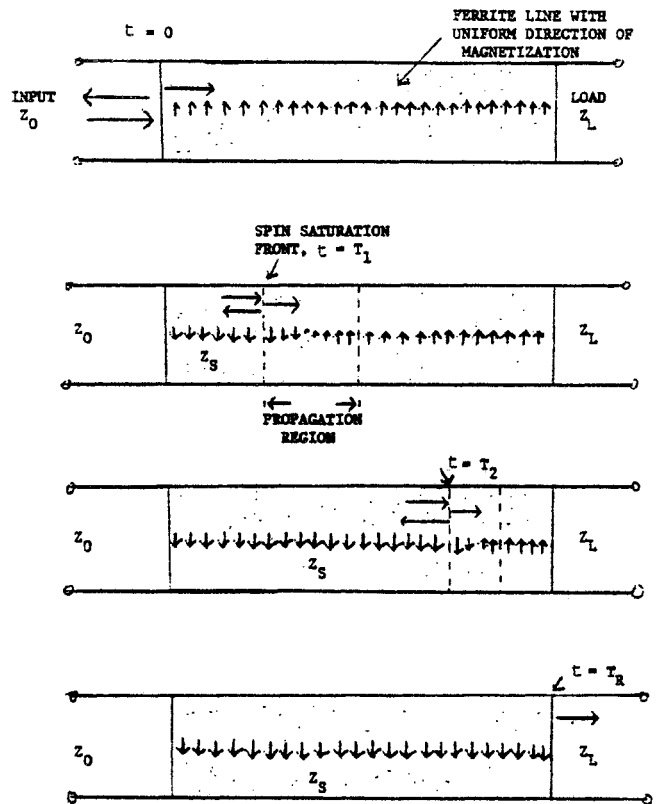4. W. C. Johnson, "Transmission Lines and Networks," McGraw Hill. 1950.

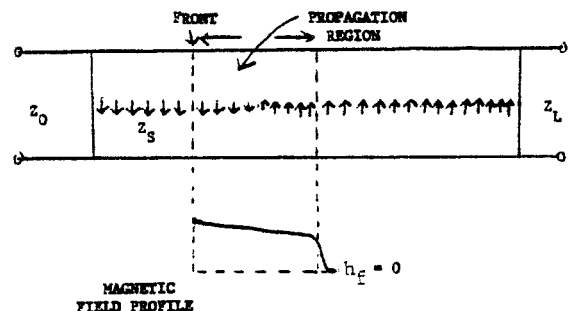Fig. 1. Motion of Spin Saturation Front in Ferrite Transmission Line.

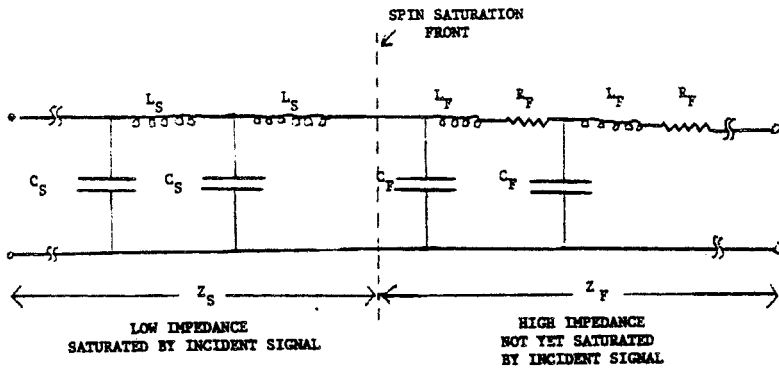Fig. 2. Propagation Region in Ferrite Transmission Line.

Fig. 3. Equivalent Circuit of Ferrite
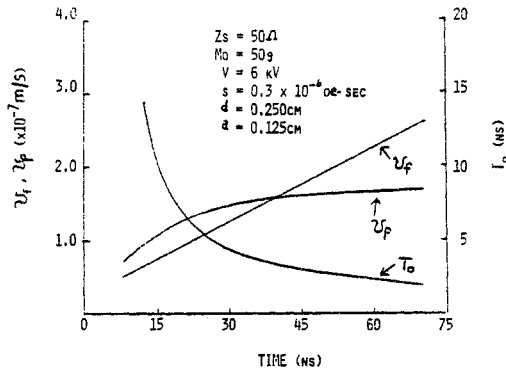Transmission Line for both
Saturated and Unsaturated Regions.

$Z_s = 50\,\Omega$
$M_0 = 50_9$
$V = 6$ kV
$s = 0.3 \times 10^{-6}$ oe-sec
$d = 0.250$cm
$a = 0.125$cm

TIME (NS)

Fig. 4. Variation of Spin Saturation
Front Velocity (v_f), Phase
Velocity (v_p), and Switching
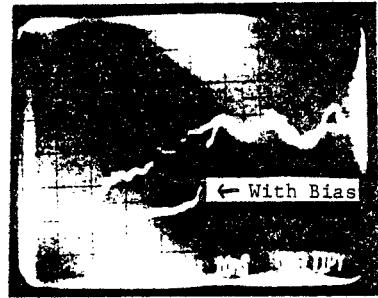Time (T_o) as Function of Time
for 70 ns Ramp Risetime.

← With Bias

Fig. 6. Pulse Waveforms at Output With
and Without Magnetic Field Bias
Horizontal: 10 ns/cm
Vertical: 1 kV/cm
Voltage on 50 Ω PFN: 6 kV.

50 OHM
CABLE NETWORK

FERRITE
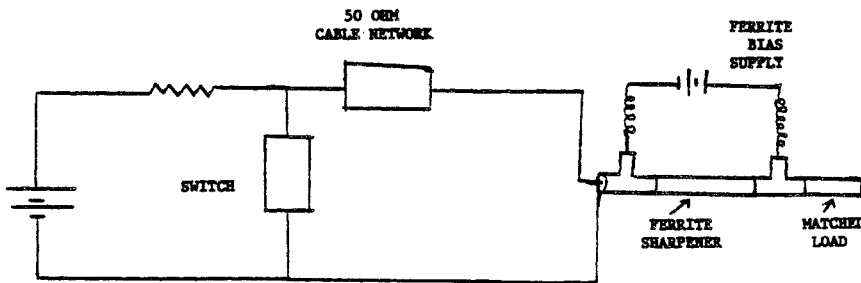BIAS
SUPPLY

SWITCH

FERRITE
SHARPENER

MATCHED
LOAD

Fig. 5. Experimental Test Circuit for
Ferrite Pulse Sharpener.